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Title: Condensed-matter injection technologies for magnetic fusion

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Condensed-matter injection technologies for magnetic fusion[1]

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Research proposed: We propose R&D and applications of matter injection technologies and especially condensed-matter injection technologies because of their growing importance to magnetic fusion. The possible R&D directions include but are not limited to A.) Different kinds of materials and structured materials to be injected into fusion plasmas for edge-localized mode (ELM) pacing; B.) New mass acceleration schemes that will allow injection speeds above 0.5 km/s and high repetitive injection rate (1 kHz and above for pulsed injections, or cw injections with flexible injection timing and duration), and C.) Improvement upon existing or development of alternative methods to control the amount of mass and the timing of injection precisely. Such R&D can take advantage of the advances from other fields such as electrostatic dust accelerators, pulsed matter launching systems with high-repetitive rates, and existing or new micro- and nano-material synthesis schemes. High-speed (one millisecond or less temporal resolution), high spatial resolution (sub-mm) imaging techniques can play important roles in such R&D[2].

Background: Matter injection into magnetic fusion plasmas comes in a variety of forms such as neutral beam injection, gas puffing, pellet injection, dust injection, granule injection, etc. Plasma injection concepts such as plasma jets and compact toroid injection also exist but they have not been validated for magnetic fusion applications yet. We emphasize condensed matter injection (CMI) technologies here which can deliver an amount of mass comparable to the total plasma mass inventory within a certain time window, typically one millisecond or less, or the mass injection rate comparable to the mass loss rate, which may be described as the plasma mass inventory divided by a characteristic time constant. In an ITER-like plasma, the total plasma mass is about 0.5 g. The characteristic time constants of interest (τ_0) include an ELM mode growth time or time related to disruptions. For disruption mitigation, τ_0 , determined by the growth time of global MHD instabilities, is on the order of 10 ms. For ELMs control, τ_0, in the range of 10^{-3} to 1 ms, is related to the growth time of ELMs. In terms of technological maturity, pellet injection in various forms and gas puffing have been routinely used in magnetic fusion. Lithium granule injectors, one of the latest members of the injector family, have caught much attention due to recent ELM-related experiments in EAST and DIII-D, and their unique ability to inject non-cryogenic low-Z matter.

So far, none of the mass injection techniques is suitable for all the applications. Neutral beam injection, being able to achieve neutral atom speeds above 10^3 km/s, is limited in the amount of mass deliverable due to the space-charge-limited current at the ion source. Pellet injection can deliver a large amount of mass much greater than 100 times the total

[1] A whitepaper submitted to DoE/FES Workshop on Transients, Greenfield/Nazikian, (2015);
[2] Wang, et al., *Rev. Sci. Instrum.* **85** 11E805 (2014).

plasma mass, sufficient for disruption mitigation but the speed of injection is limited to less than 0.5 km/s. Gas puffing has limited penetration depth in fusion plasmas. Granule injectors using a rotating impeller have been able to inject particles up to 1 mm with a speed up to ~ 100 m/s, both the injection frequency and the amount of mass injected could be improved. Dust injection has demonstrated a few km/s for granular matter less than 0.1 mm in size and the technology is yet to be used in magnetic fusion.[3]

Progress since ReNeW: We only highlight two recent results here,[4] both of which are related to ELMs control and as a result heat flux onto plasma facing components and impurity generation at the plasma boundary. In recent DIII-D experiments, high repetition rate injection of deuterium pellets from the low-field side (LFS) was shown to trigger ELMs more than 10 times the natural ELM frequency in H-mode deuterium plasmas. This work demonstrated that shallow, LFS pellet injection can dramatically accelerate the ELM cycle and reduce instantaneous energy fluxes on plasma facing components. Real-time control of ELMs is possible in ITER based on this work. Lithium granule injectors were first successfully used in EAST and then in DIII-D. Sub-mm lithium granules were injected by a simple rotating impeller at speeds of 10s of m/s in both experiments. ELMs were triggered with near 100% efficiency. Using materials other than cryogenic deuterium pellet opens door to a variety of materials for plasma Z-control and wall conditioning.

Opportunities, national and international context: R&D related to plasma-material interaction (PMI) is a new frontier in magnetic fusion in the ITER era.[5] CMI can play active roles in PMI research, extending their traditional roles in fueling and diagnostics. Possible new applications include wall and plasma conditioning that allow impurity control and H-mode operations, ELM control and disruption mitigation. ELM control, including both ELM pacing and suppression, could have important consequences for high-performance fusion plasma operations. Reliable technology for disruption mitigation is one of the greatest challenges in ITER-like operations. On-going and near future experiments in DIII-D, NSTX-U and outside the US provide the necessary environment for the proposed R&D before ITER comes online.

Anticipated results and impact on future activities: Experiments can be extended to examine the effects of different materials in addition to ^{2}H and ^{7}Li, injection speeds, injection frequency, and mass rate to trigger or suppress ELMs. To demonstrate injection technologies that can deliver at least 50 g of mass at a speed above 0.5 km/s will be an important milestone for disruption mitigation in ITER. Improving upon existing methods such as cryogenic pellets and granule injectors will continue. Meanwhile, non-traditional approaches such as electrostatic injectors at high current, pulsed compact injectors at high-repetitive rate (above 1 kHz) provide new research opportunities. New injector development can be coupled with advances in new materials and in particular micro- and nano-structured materials to broaden the material choices. These materials will not only

[3] Ticos, et al, *Phys. Rev. Lett.* **100**, 155002 (2008).
[4] Mansfield, et al, *Nucl. Fusion* **53,** 113023 (2013); Baylor, et al, *Phys. Rev. Lett.* **110**, 245001 (2013).
[5] Lorte, et al, *Nucl. Fusion* **54,** 033007 (2014);

allow higher injection velocities, they can also contribute to core plasma impurity (Z_{eff}) control, particle recycling and wall conditioning. Mass injector experiments will also generate experimental data for dust transport simulation and dust control, a topic of growing interest.